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TECHNICAL REPORT BRL-TR-3217

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TEMPERATURE MEASUREMENTS OF 30-MM
REGENERATIVE LIQUID PROPELLANT GUN
(RLPG) FIRINGS

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MARCH 1991



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13. ABSTRACT (Maximum 200 words) Gas phase temperature measurements were made during 30-mm regenerative liquid propellant gun (RLPG) firings with an invasive spectroscopic technique developed at the Ernst Mach Institute. The technique was based on measuring the brightness temperature of the combustion gas with an optical probe emission gage. Planck's distribution of blackbody emission was used as the basis for calibrating the emission gage, thus providing a theoretical basis for extrapolating the response of the gage beyond the maximum calibration temperature. The propellant used in the tests was LGP 1845, which has an adiabatic flame temperature of 2,592 K. The spectroscopic technique, calibration procedure, and experimental results are discussed. The results yielded maximum temperatures between 2,200 K and 2,450 K, or 5 to 15 percent below the adiabatic flame temperature. The results show fair qualitative agreement with a lumped parameter computer model.				
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I. INTRODUCTION

Temperature measurements of the gas phase during the combustion of gun propellants in closed chambers and guns has been a goal of ballisticians for many years. Studies to measure the gas phase temperature have been underway for almost half a century, although most of the activity has been concentrated in the last two decades. A summary of the recent work can be found in Reference 1.

Work during the seventies and early eighties by Klingenberg²⁻⁵ at the Ernst Mach Institute led to an invasive spectroscopic technique for measuring the gas phase temperature in a high pressure-high temperature environment. This technique uses an optical probe, called an emission gage, which measures the emission directly. Based on comparisons of the color temperature and the brightness temperature, Klingenberg concluded that the emission inside gun type combustion chambers approaches blackbody conditions. Under blackbody conditions, the brightness temperature and the absolute temperature are equivalent. Therefore, the absolute temperature can be obtained directly from the emission data.

It should be pointed out that temperature measurement methods based solely on spectral emission data require a continuous distribution of radiation over an infinite frequency range. This requirement may be relaxed if two conditions are met. First, the measurement may be made over a narrow band in the continuous radiation assuming thermal equilibrium conditions. The second requirement is that the gas volume in the field of view is homogeneous and at a uniform temperature. The presence of unburned solids or liquid drops may not satisfy this requirement. Despite these possible limitations, the experimental temperatures obtained by Klingenberg generally agreed to within 10% of the theoretical adiabatic flame temperatures.

This study is concerned with improving the emission gage and calibration procedure of the spectroscopic technique and applying the technique to liquid propellant guns. This paper outlines a new calibration procedure using Planck's Radiation Law. The new procedure needs fewer calibration measurements. Also, the procedure is theoretically more accurate at higher temperatures than previous curve fitting procedures. The new procedure was applied to measurements taken in a 30-mm Concept VI Regenerative Liquid Propellant Gun (RLPG).

II. CALIBRATION

A. Calibration Measurements:

Figure 1 illustrates the calibration setup. First, an image from the tungsten filament lamp was focused on the ground glass plate (diffuser). The ground glass diffused the light and acted as a screen for the image from the filament. The brightness temperature of the image was determined using a calibrated optical pyrometer. After obtaining a relationship between the lamp current and the brightness temperature, the pyrometer was removed and the emission gage was positioned against the image on the ground glass and a flexible fiber optic was connected to the rear of the gage. The flexible fiber optic passed the radiated emission through a narrow band interference

filter and then to the photomultiplier. A filter of 647.1 ± 5 nm was used in the tests reported here. The photomultiplier converted the radiation into a voltage which was recorded on a Nicolet oscilloscope. From the output of the photomultiplier a relationship of voltage verses lamp current was obtained. Comparing the relationships between brightness temperature verses current and photomultiplier output verses current provided a final relationship between brightness temperature and photomultiplier output.

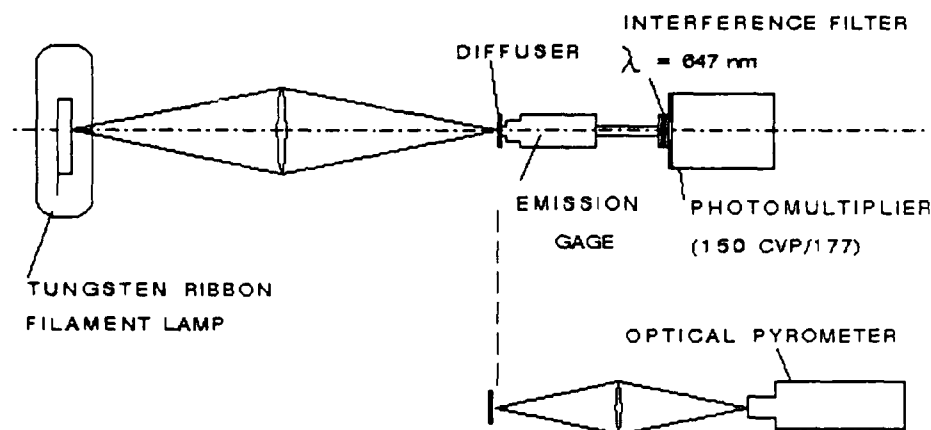


Figure 1. Calibration Setup

B. Planck's Radiation Law:

Previous methods for calibrating the emission gage were based on developing various relationships between the brightness temperature and photomultiplier output using standard curve fitting routines, such as a power law or logarithmic fit.^{6,7} These methods are tedious and time consuming because of the large number of measurements required to generate a calibration profile. Also, a theoretical basis for extrapolating beyond the maximum calibration temperature was not developed, limiting the procedure to the calibration limits. The procedure reported here describes a calibration technique designed to overcome both previous concerns. The technique, based on Planck's Radiation Law, requires fewer calibration measurements and extrapolation to higher temperatures is theoretically more accurate. The following outlines the derivation of the necessary relationships.

Planck's Law⁸ gives the radiant energy emitted by a blackbody:

$$J_{bl} = \frac{C_1}{\lambda^5 [\exp(C_2/(\lambda T)) - 1]}, \quad (1)$$

where J_{b1} is the amount of energy radiated at wavelength λ per unit area per unit time and T is the absolute temperature of the blackbody. C_1 and C_2 are the first and second radiation constants. Values for C_1 and C_2 are

$$C_1 = 3.7403 \times 10^{-12} \text{ Watt-cm}^2,$$

$$C_2 = 1.438 \text{ cm-K.}$$

The spectral emissivity, ϵ , of bodies other than blackbodies, describes the fraction of actual energy emitted by the surface of a body compared with an ideal blackbody. For the case under consideration, the gases approximate a blackbody² or $\epsilon \approx 1$. For such conditions, the brightness temperature approximates the absolute temperature and corrections for emission are not required.

To apply Planck's Law to the temperature measurement technique, the photomultiplier output, in volts, must be converted to energy per unit area per unit time. The conversion uses the experimental calibration measurements. Since the sensor area is assumed to be constant and the wavelength of the emission is restricted to a narrow bandwidth by a filter, a coefficient may be introduced to convert the photomultiplier output to the required units. With the conversion coefficient introduced, Planck's Law becomes

$$J_{b1} = V_{PM}/A = \frac{C_1}{\lambda^5 [\exp(C_2/(\lambda T)) - 1]}, \quad (2)$$

where V_{PM} is the photomultiplier output and A is the conversion coefficient. Solving for A gives the following:

$$A = \frac{\lambda^5 V_{PM} [\exp(C_2/(\lambda T)) - 1]}{C_1}. \quad (3)$$

The conversion coefficient A can be calculated since C_1 , C_2 , and λ are known and V_{PM} and T are obtained during calibration. Rearranging Equation 3 to solve for temperature gives the following:

$$T = (C_2/\lambda) / \ln[A C_1 / (\lambda^5 V_{PM}) + 1]. \quad (4)$$

Equation 4 is the calibration equation using Planck's Radiation Law solved for temperature in terms of photomultiplier output, known constants, and a calibration coefficient.

III. EXPERIMENTAL

A. Emission Measurement:

Figure 2 shows a schematic of the emission gage (supplied by the EMI, Germany) used for the temperature measurement. A bundle of approximately 25 parallel quartz optical fibers were fixed into the axis of a steel tube using epoxy. Each fiber is 0.1 mm in diameter. The bundle has a diameter of 0.5 mm with a surface area of 0.19 mm² and an aperture angle of 25°. This design is

resistant to pressures up to 300 MPa. The transparency of the optical fibers restrict transmittance to visible light in the spectral region between 400 and 800 nm. The emission gage mounts into a standard Kistler 607 pressure gage port and protrudes into the combustion chamber about 7 mm to minimize boundary layer effects. A flexible fiber-optic cable transmits the emission detected by the gage to an interference filter (647.1 ± 5 nm). After passing through the filter, the emission is led to a photomultiplier (type 150 cvp/177). The photomultiplier converts the emission to a voltage, which is recorded on an analog tape.

In previous tests made at the Ballistic Research Laboratory (BRL) the temperature recorded was higher than the adiabatic flame temperature of the propellant. It was determined that the ends of the fiber optic bundle of the emission gage would burn during the combustion cycle of a test. Therefore, the detected emission was higher than what the gage was calibrated for, resulting in a higher recorded temperature. To protect the end of the fiber optic bundle a thin (0.254 mm) cover glass was epoxied on the face of the emission gage. The glass cover also enabled the gage to be reused, which was not possible with an unprotected gage.

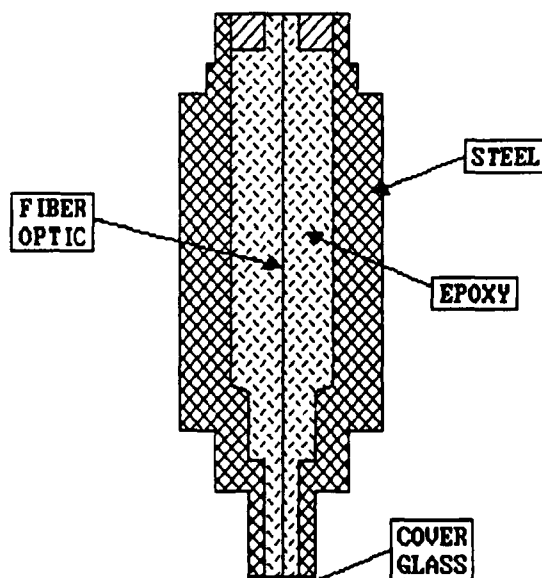


Figure 2. Emission Gage

B. Concept VI RLPG:

Temperature measurements were made during test firings of a 30-mm Concept VI RLPG. A schematic of the Concept VI RLPG is shown in Figure 3. This concept uses an in-line, annular regenerative piston to pump a liquid monopropellant into the combustion chamber. The propellant enters the chamber as an annular sheet, where the propellant breaks up and burns. A complete description of the Concept VI RLPG can be found in Reference 9.

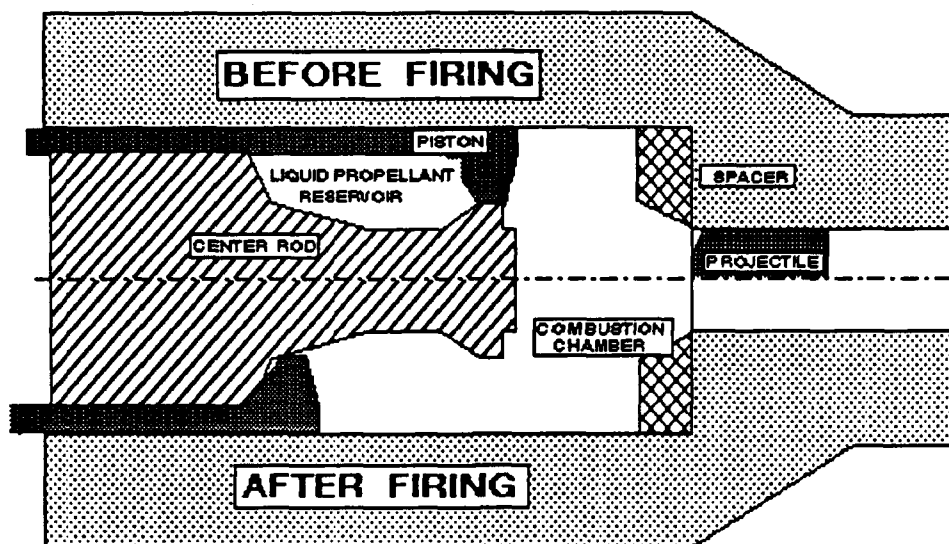


Figure 3. Schematic of the Concept VI RLPG.

C. Liquid Propellant:

The liquid propellant used in the tests was Liquid Gun Propellant (LGP) 1845. Table 1 summarizes the thermochemical properties of LGP 1845.¹⁰

TABLE 1. Thermochemical Properties of LGP 1845 at a Loading Density of 0.2 g/cm³

TEAN (wt%)	HAN (wt%)	Water (wt%)	Density (g/cm ³)	Impetus (J/g)	Flame Temp (K)	Gamma
20.0	63.2	16.8	1.45	934.2	2592	1.218

IV. RESULTS and DISCUSSION

A. Calibration:

Table 2 lists the calibration measurements for Test No. 415-47. For Test No. 415-47 the emission gage was calibrated to a temperature of 2640 K, so extrapolating beyond the maximum calibration temperature was not needed. We have experienced a "lamp burn out" at roughly 2500 K. For this reason all lamp calibration temperatures are normally kept below 2300 K and extrapolation beyond the maximum calibration temperature is required. The lower limit of our temperature measurement system is about 1850 K, the temperature at which emission can be detected in the visible range at the recording wavelength.

The conversion coefficient A was obtained by solving Equation 3 with the values in Table 2. The average value of the conversion coefficient was used to account for minor errors in the readings. A calibration curve was generated using the average value for the conversion coefficient and compared to the original calibration measurements. Figure 4 shows the calibration curve for Test No. 415-47 and the calibration measurements.

TABLE 2. Calibration Measurements for Test No. 415-47

Photomultiplier output (mV)	Temperature (K)	Conversion coefficient, A $\times 10^{-13}$ ($\text{m}^3\text{V/W}$)
75	2180	6.1
120	2280	6.3
172	2380	6.0
231	2430	6.6
315	2500	7.0
430	2570	7.5
538	2640	7.4
		average A = 6.7

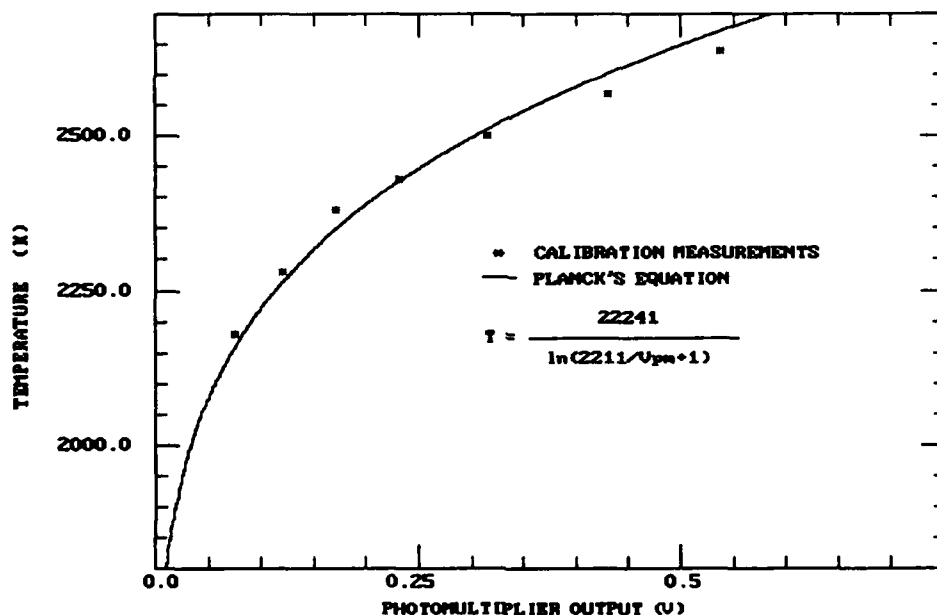


Figure 4. Calibration Curve for Test No. 415-47.

B. Chamber Pressure:

Figure 5 shows the combustion chamber pressure for Test No. 415-47. A solid propellant igniter, 3.5 grams of IMR 4350, was used to initiate the ballistic process and accounts for the early pressure rise. The pressure increases about 20 MPa during the first 3.5 ms due to the solid propellant

igniter. After 4 ms, the combustion of the liquid propellant begins and the pressure increases to a maximum of about 150 MPa during the next 6 ms. After all of the liquid has been injected and consumed, the pressure decreases, corresponding to an adiabatic expansion of the gases. The pressure oscillations seen in the pressure trace are typical in tests when LGP 1845 is used as a propellant.

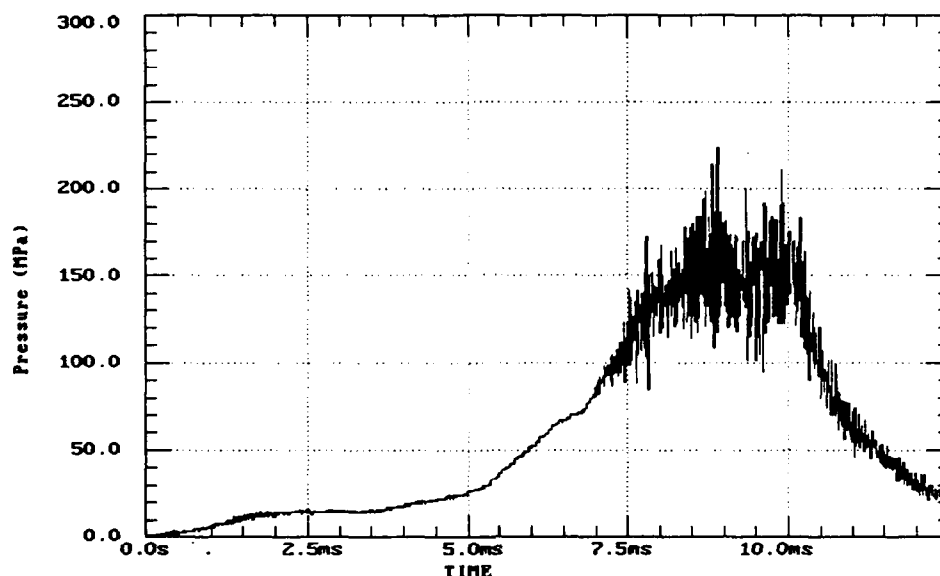


Figure 5. Chamber Pressure for Test No. 415-47.

C. Temperature Measurement:

Figure 6 shows the recorded temperature for Test No. 415-47. The initial temperature rise, less than 1 ms into the ballistic cycle, is believed to be caused by interference from the firing pulse (350 Volts for 0.5 ms) which is used to ignite an electrical primer. The primer ignites the solid propellant in the igniter and the process continues as described above. The temperature recorded between 1 ms and 2.5 ms corresponds to the expansion of the igniter gases into the combustion chamber. The transition period between the solid and liquid propellant combustion occurs between 2.5 ms and 5.0 ms. During this period very little combustion takes place in the chamber and, as a result, the visible emission decreases. Hence, the temperature appears to decrease also. After the start of the liquid propellant combustion, the temperature rises rapidly and reaches a plateau and remains high during the injection and combustion process. The temperature then decreases corresponding to the expansion of the combustion gases. All of the liquid propellant has been injected and consumed by about 10 ms. The maximum temperature was roughly 2450 K, or 5.5% lower than the adiabatic flame temperature, 2592 K.

Table 3 lists the maximum temperature and pressure measurements from five tests using the modified emission gage with a glass cover to protect the fibers from burning. Various test conditions were changed between the tests as part of another study on pressure oscillations and will not be described

here.¹¹ The rise and fall trends in the data from Test No. 415-47 are similar to the other four tests summarized in Table 3 with the exception of the peak magnitudes. One possible explanation for the decreasing trend in the temperature is that the LP injection sheet thickness was increased in Test Nos. 49 & 50 and again in Test 51. The LP injection sheet thickness is the thickness of the annular gap between the center control rod and the injection piston (Fig. 3). In Test Nos. 47 & 48 the sheet thickness was 1.75 mm. In Test Nos. 49 & 50 it was 2.39 mm and in test 51 the sheet thickness was 3.0 mm. Figure 7 shows a plot of the temperature vs. LP injection sheet thickness for the five tests. Additional testing is planned to validate the decreasing trend in temperature with increasing LP injection sheet thickness.

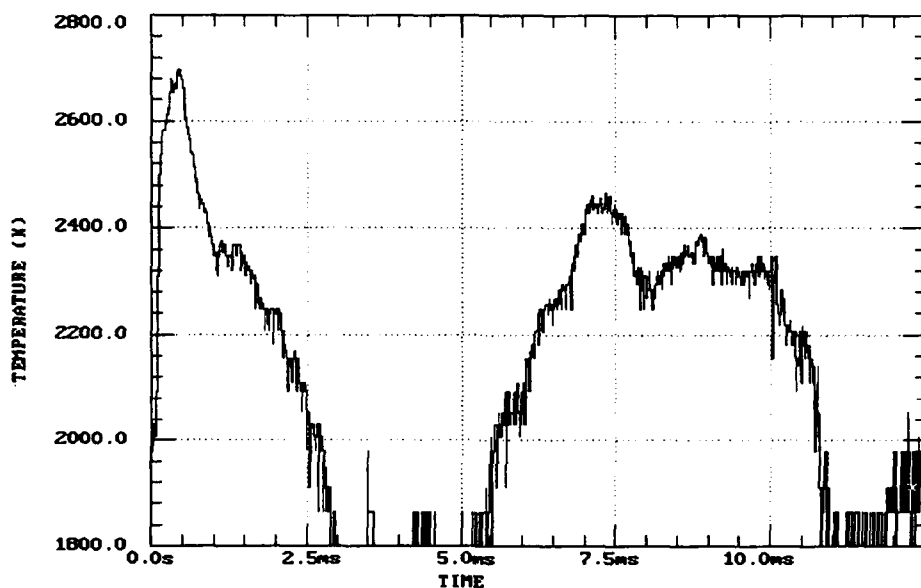


Figure 6. Experimental Temperature for Test No. 415-47.

TABLE 3. Results of Five Maximum Temperature and Pressure Measurements

Test No.	Temperature (K)	Pressure (MPa)
415-47	2450	160
415-48	2320	180
415-49	2300	200
415-50	2200	170
415-51	2200	230

V. PRESSURE - TEMPERATURE MODEL COMPARISON

Figure 8 shows the comparison between the recorded pressure and a lumped parameter model.^{12,13} The parameters for the model are adjusted so the model pressure matches the experimental chamber pressure closely. Excellent agreement is noted. Figure 9 shows the comparison between the recorded temperature and the lumped parameter model. Qualitatively the agreement between the model and experiment is fair. The maximum computed and

experimental temperatures are similar, however, the model predicts a temperature rise, due to the combustion of the LP, about 1 ms before the rise in the experimental data. This lack of agreement on the temperature rise is presently under study.

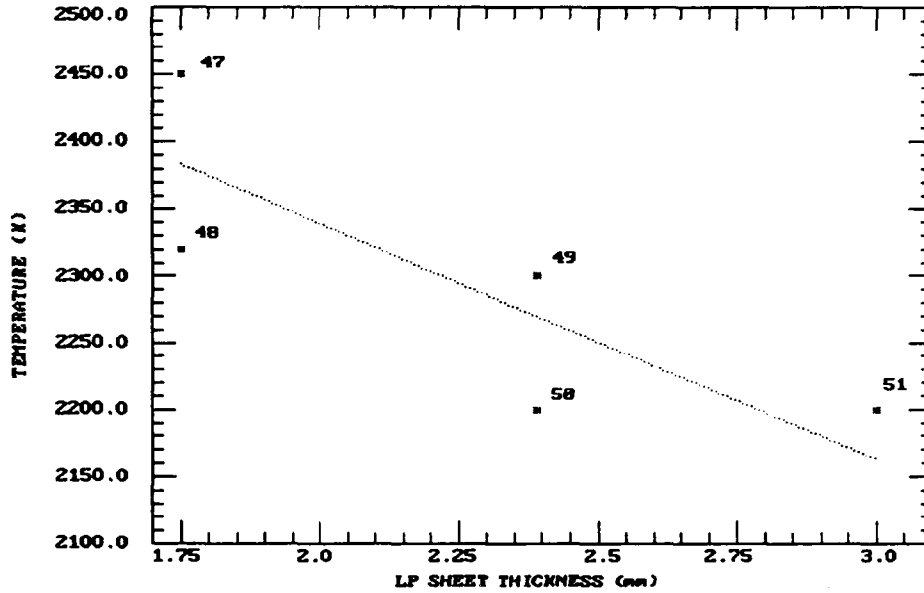


Figure 7. Temperature vs. LP Sheet Thickness for Tests 415-47 to 415-51.

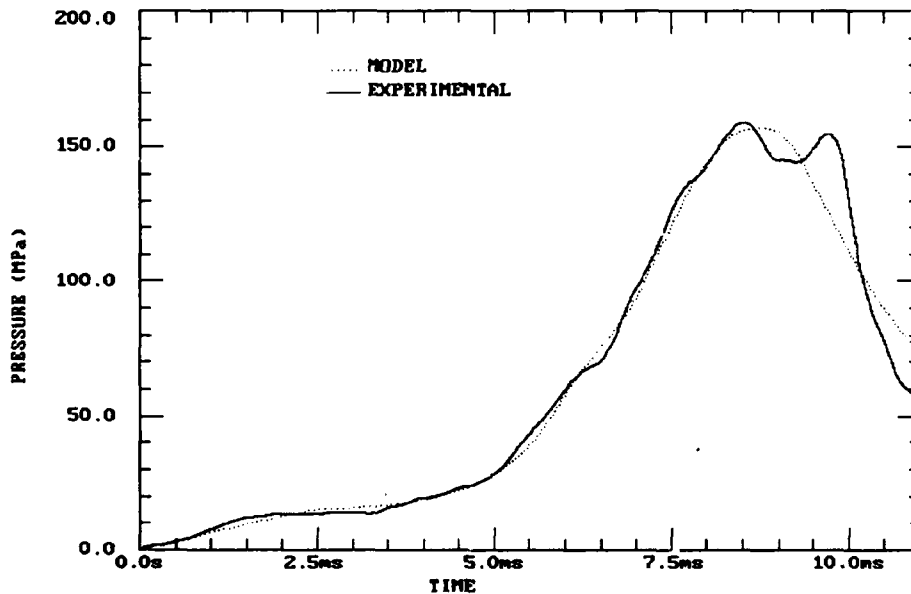


Figure 8. Comparison between Lumped Parameter Model and Experimental Pressure for Test No. 415-47.

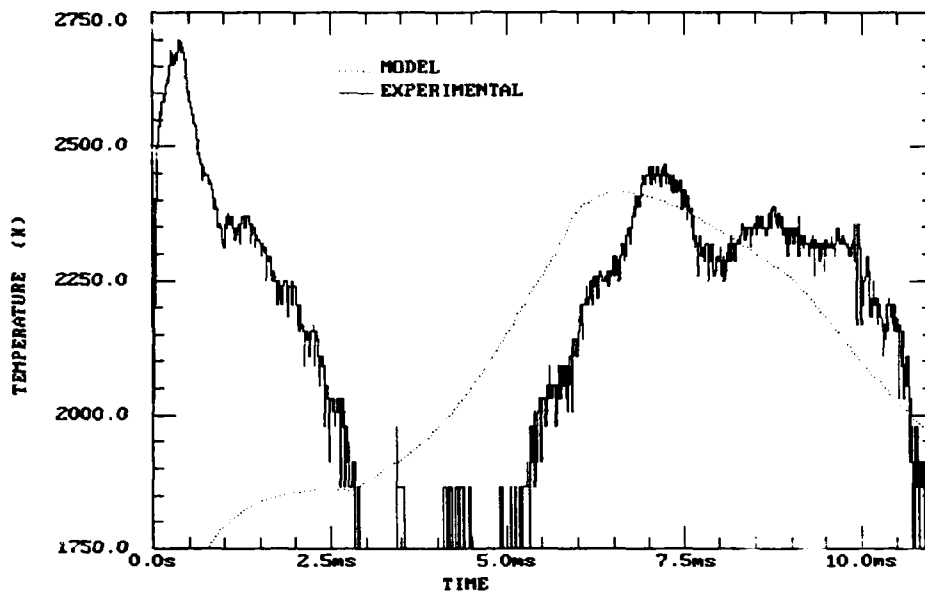


Figure 9. Comparison between Lumped Parameter Model and Experimental Temperature for Test No. 415-47.

VI. CONCLUSIONS

A modified emission gage was successfully used for measuring the chamber temperature during test firings in a 30-mm Concept VI RLPG. The modification consisted of a protective glass cover on the face on the emission gage. The tests demonstrated that the glass cover protected the gage from the high temperature gases during the gun firing and eliminated the earlier problem related to the burning of the optical fibers. Additionally, a new calibration procedure based on Planck's Radiation Law was successfully applied. The procedure permitted an extrapolation of the test data beyond the temperature limits of the available calibration instruments. Temperatures between 2200 K and 2450 K, or 5 to 15 percent below the adiabatic flame temperature were recorded. The temperature of the combustion gases appears to decrease with increasing LP injection sheet thickness. Additional testing is planned to verify this trend.

The measured temperature data were compared with predicted chamber temperature based on a lumped parameter model. Only fair agreement was obtained. The increase in temperature due to the burning of the injected liquid propellant occurred in the model about 1 ms before the rise in the experimental data. This lack of agreement is presently under study.

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